Honeywell

# Ceramic Technology Development

## In Support Of

## The DOE Advanced Microturbine Systems Initiative

**Hot Section Components in Advanced Microturbines** (Subcontract #4000000986)

**High-Velocity High-Pressure Burner Rig** (Subcontract #40000006367)

**Advanced Microturbine System** (Cooperative Agreement #DE-FC02-00CH11061)

## Honeywell Engines, Systems & Services

**Dr. Bjoern Schenk (Advanced Technology)**
**Dr. Thomas Strangman (Materials & Process Engineering)**
**Dr. Chien-Wei Li (Honeywell Labs)**
**Dr. James Wimmer (Ceramic Components)**

**Peer Review of the Microturbine and Industrial Turbine Programs**
**Fairfax, VA**
**March 12-14, 2002**

# Principal Commercialization Barriers

- Inadequate oxidation protection technology
- Inadequate facilities available to screen candidate substrate material and novel coating systems prior to high risk engine tests
- Immature low-cost near-net-shape fabrication processes
- Insufficient publicly available material design database of latest ceramic material vintage

**Honeywell's DOE-Funded Program Suite Addresses All Barriers And Enables Accelerated Commercialization of Ceramics in Small Gas Turbines**

# Hot Section Components in Advanced Microturbines

## Subcontract No. 4000000986 from UT Battelle LLC

# Motivation

- Low-Velocity Burner Rig Testing Revealed Paralinear Recession of Silicon-Based Materials in Microturbine Environments
- Allison Engine Tests Confirmed Expected Excessive Material Recession of Uncoated AS800 Nozzles
- Keiser Rig Testing Indicated Degradation of Uncoated AS800 Even in Quasi-Stagnant Moist Environment
- Initial Testing of Honeywell EBC Indicated Significant Benefit to Environmental Resistance
- Coating Process Development and Environmental Resistance Data on Coated AS800 and AS950EXP Needed

# Program Has Two Phases

- Phase I (3 months)
  - Task 1: Advanced Microturbine Scoping Studies and Research Plan
- Phase II (21 months)
  - Task 1: Environmental Effects (Uncoated)
  - Task 2: Technology Assessment for Environmental Protection (First Generation Environmental Barrier Coatings)
  - Task 3: Rapid Prototyping (Discontinued)
  - New – Task 4: Substrate Material Specimens Preparation for Next Generation EBC Development
  - New – Task 5: AS950EXP Gelcast Substrate Process Refinement

# Microturbine Conditions Required to Guide Material Test Matrix

## Microturbine Hot Section Environment

- Temperature
- Total Pressure
- Water Vapor Content
- Gas Velocity

## Survey of Microturbine OEMs

- Honeywell Power Systems
- Capstone
- Ingersoll Rand
- Williams
- Allison
- Teledyne
- UTRC (verbal input)
- Elliot Turbine (declined to provide information)
- GE (no response)

# Strawman Envelope Used to Guide Discussions

| PARAMETER | STRAWMAN | PROPOSED |
|---|---|---|
| TEMPERATURE | 1900 – 2300°F | 1800 - 2400°F |
| TOTAL PRESSURE | 5 – 10 ATM | 4 -10 ATM |
| WATER VAPOR | 5 – 15% | 3 – 20% |
| GAS VELOCITY | 0 – 250 fps | 0 – Mach 1* |

*Limited by available rig capability

- **Small Modifications to Strawman Envelope Satisfy Customer Requirements**

# Companies Also Surveyed on Microturbine Component Needs

Engine Company

| | Inserted Axial Blades | Integral Axial Rotor | Integral Radial Rotor | Individ Nozzles | Integral Axial Nozzle | Integral Radial Nozzle | Turbine Shroud | Combustor |
|---|---|---|---|---|---|---|---|---|
| 1 | | |  | | |  |  |  |
| 2 | |  |  | |  |  |  |  |
| 3 | |  | | |  | |  |  |
| 4 |  |  | |  |  | |  |  |
| 5 | | |  | | |  |  |  |
| 6 | | |  |  | |  |  | |
| 7 | |  | | |  | | | |

Honeywell

# Materials Selected for Environmental Effects Testing

| MATERIAL | FABRICATION PROCESS | RATIONALE FOR MATERIAL SELECTION |
|---|---|---|
| AS800 | Slipcast | Currently Used in RR Allison 501k Turbine Nozzles, Solar Centaur Turbine Blades, and APU Hot Section Components. |
| AS800 | Gelcast | Near-net-shape forming process. Process can be automated. |
| AS950EXP | Slipcast | Baseline comparison with AS800. |

**Focus on As-Processed Surfaces**

# ORNL to Provide Environmental Testing and Characterization

- **Keiser Rig**
  - Hanging Samples Approximately 25 x 50 x 3 mm
  - Can Section Each Into 3 Mil-B Flexural Bars
- **High & Low Flow Rigs**
  - Availability/Timing Unknown
- **Recommendations for Initial Environmental Test Matrix**
  - 3 temperatures - 1800, 2100, 2400°F
  - 3 water vapor contents - 0.3, 1, 2 atm
  - time - 500, 1000, 1500, 2000 hr
  - Slipcast AS800, Gelcast AS800, Slipcast AS950EXP
  - Variation of Total System Pressure Required?

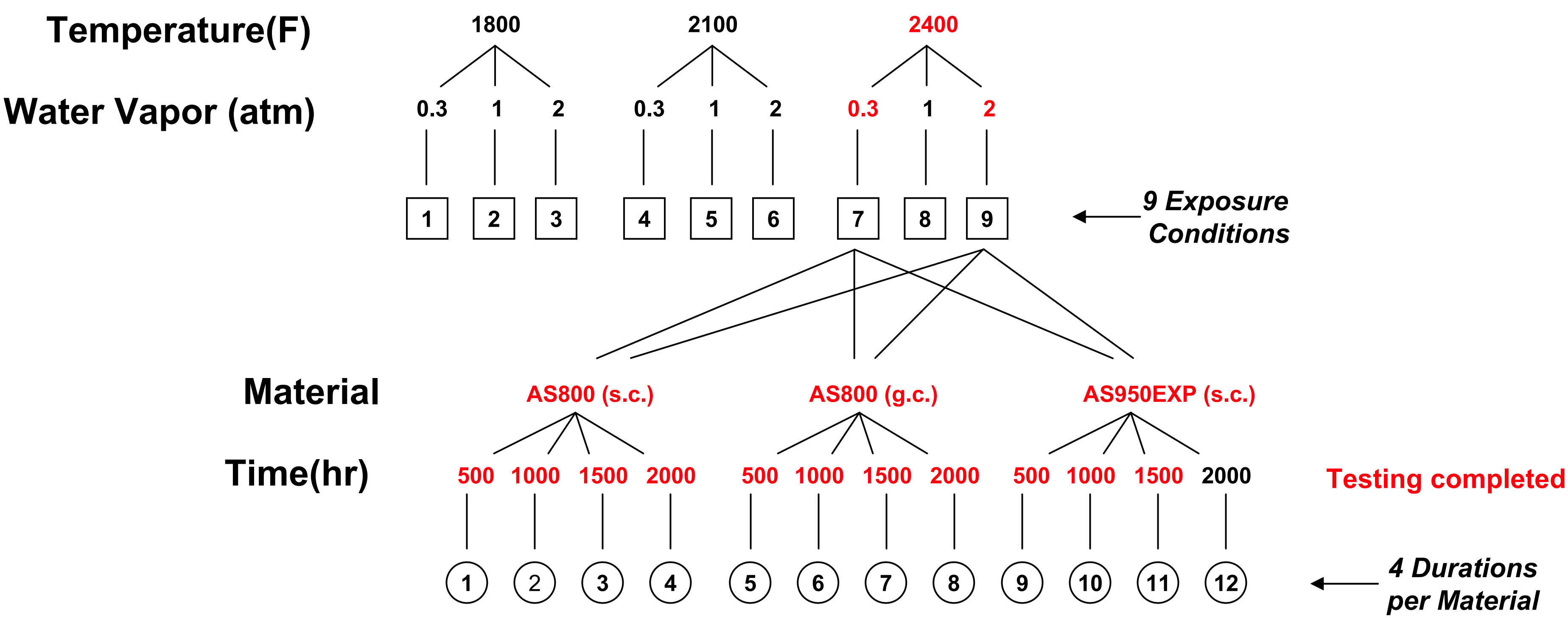
# Effect of Total System Pressure on Recession

- Screening Experiment Conducted to Evaluate Effect of Total System Pressure (Oxygen and Nitrogen Partial Pressure) on Recession
  - Test Temperature: 2400F
  - Test Duration: 1000 hours
  - Tube #1: $N_2$ with 25vol% $H_2O$ at 8 atm total system pressure
    - $p(N_2)$ = 6 atm    $p(H_2O)$ = 2 atm    no oxygen
  - Tube #2: Air with 20vol% $H_2O$ at 10 atm total system pressure
    - $p(N_2)$ = 6.24 atm    $p(H_2O)$ = 2 atm    $p(O_2)$ = 1.68 atm
  - Slipcast AS800, Gelcast AS800, Slipcast AS950EXP
- Total System Pressure Had Negligible Effect on Silicon Nitride Oxidation Kinetics and Microstructural Damage
- Total System Pressure Eliminated As Parameter for Keiser Rig Design of Experiment

Honeywell

# Initial Test Matrix for Keiser Rig Exposure

- 8 Plates (min) of Each Uncoated Material for Each Run Required
- Coated Samples to Be Exposed in Separate Tubes at Selected Conditions for Evaluation & Comparison




Honeywell

# Phase II - Task 2: Technology Assessment for Environmental Protection (First Generation EBCs)

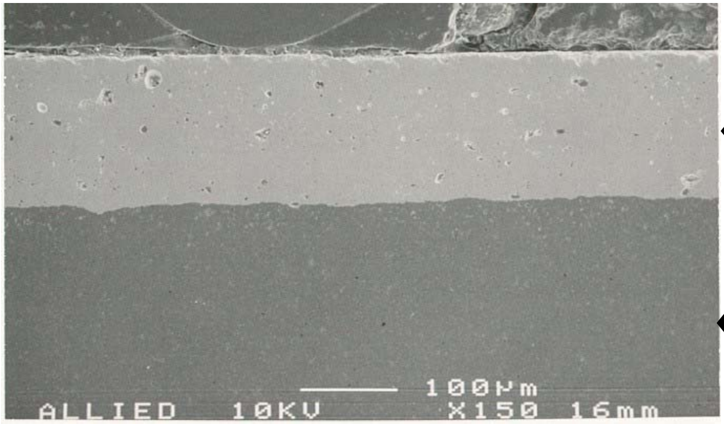
## Coating Requirements

- Thermodynamically stable in operating environment up to 1400°C
  - no significant grain growth & phase transformations
  - high stability against reactions with oxygen, water vapor, and all other constituents of and impurities contained in gas turbine combustion gas flow
  - low vapor pressure at service conditions
- Effective oxygen and water vapor diffusion barrier
- Thermal expansion similar to $Si_3N_4$ to minimize spallation potential
- Good adherence to as-processed silicon nitride component surfaces
- Chemical compatibility to substrate material
- Chemically compatible to $SiO_2$
- Applicable to complex-shaped components
- Repeatable thickness, grain size distribution, and porosity
- Reasonable small particle impact and erosion resistance
- Minimal impact on substrate strength
- Affordable

Honeywell

# EBC Has Been Applied by Air Plasma Spray (APS) and EB-PVD

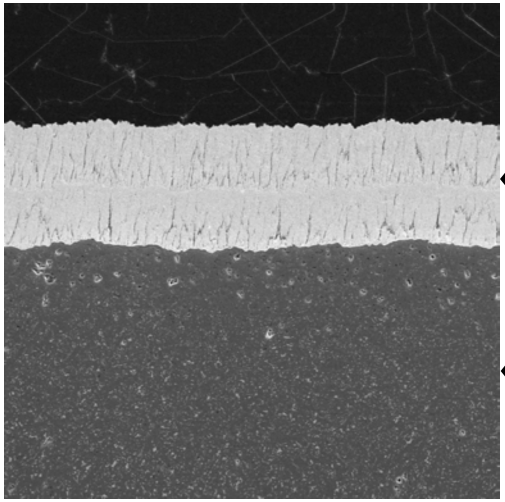
- Plasma Spray
  - Coating is Dense
  - "Low" Temperature Phase
  - Cyclic Furnace Testing Demonstrated Good Adherence




APS EBC

AS800

- EB-PVD
  - Various Trial Runs for Process Optimization in Progress
- Coatings are Thermally Treated to Characterize Grain Growth
- Coating are Thermally Cycled to Characterize Adherence



EB-PVD EBC

AS800

Honeywell

# Supplementary IR&D Work on First Generation EBCs Has Been Conducted

- Control of Phase Transformation
  - Phase Transformation at Elevated Temperatures (>2400F) Can Induce Cracking
  - Non Issue for Current Microturbine Applications, but Concern at Higher Temperatures
- Control of Grain Growth
  - Maintain Coating Strength
- Control of Thermal Expansion
  - Match CTE of Silicon Nitride
- Sprayable Powder With Tailored Compositions Demonstrated
- Tailored Compositions Improved Coating Cyclic Performance at 2400°F
- Promising Grain Growth and Transformation Inhibitors Identified
- Three Batches of Improved Compositions Were Plasma-Sprayed and Cyclic Tested
- Keiser Rig Validation in Progress

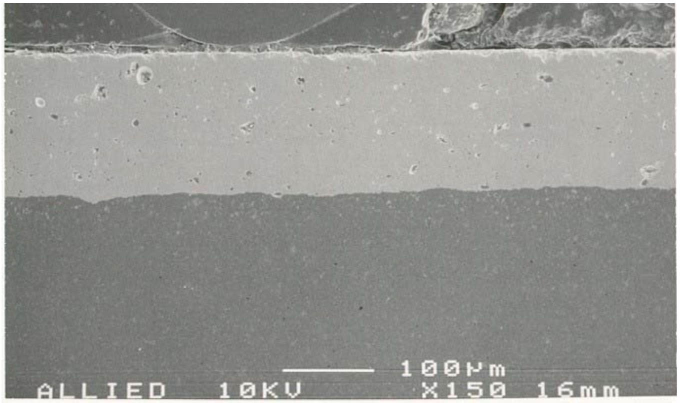
# Separate DOE-Funded R&D Program Supports APS EBC Maturation

- Identify Optimized Plasma Spray Processing Parameters
- Fundamental Understanding of Compositional Variations on Microstructure Development
- Establish Microstructure-Property Relationship
- Characterize and Understand Bonding Strength

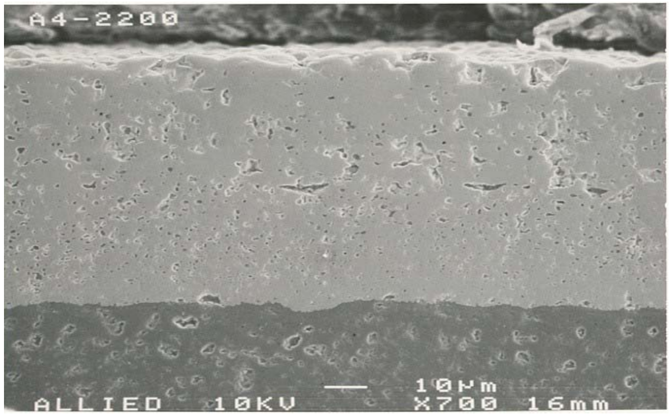
Honeywell

# First Generation EBC Development

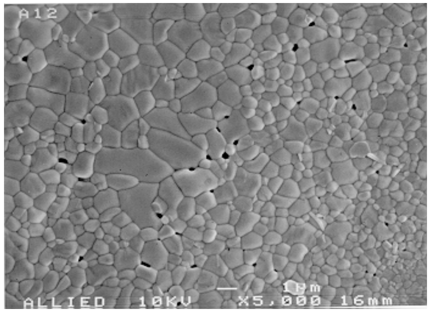
**APS EBC after testing at 2200 F/500 h/1000 cycles**



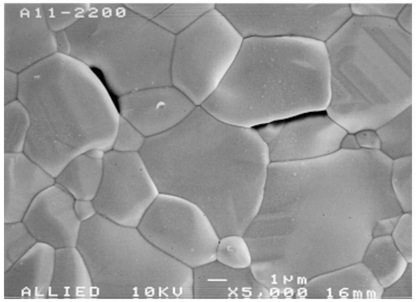

**EB-PVD EBC after testing at 2200 F/500 h/1000 cycles**




**Grain growth of EBC at high temperature**

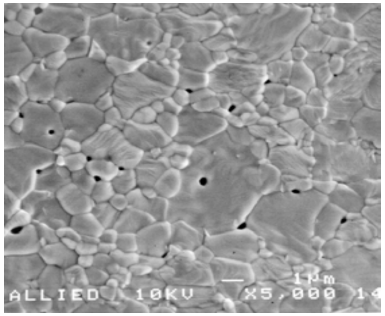



As-deposited (plasma)

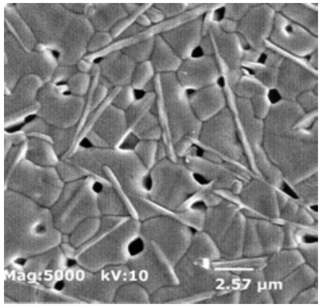



After 500 hours at 2200F

**Control grain growth of EBC by alloying**




Composition A



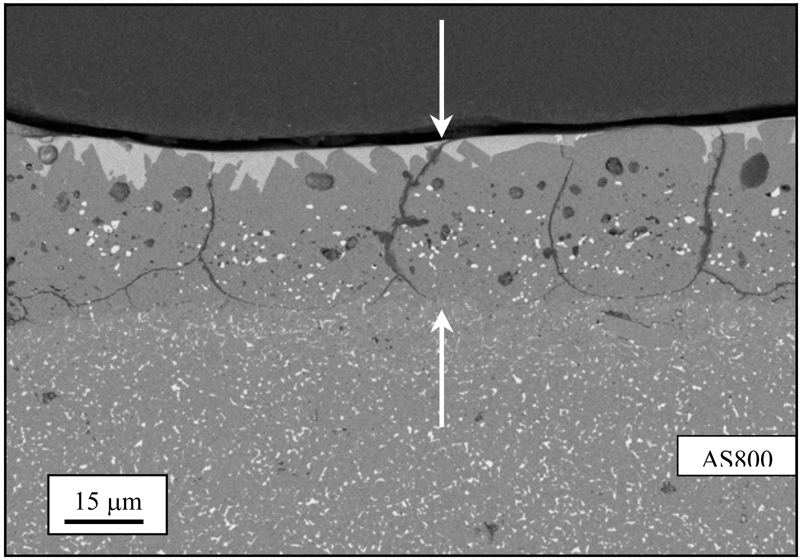

Composition B
(from liquid precursor)

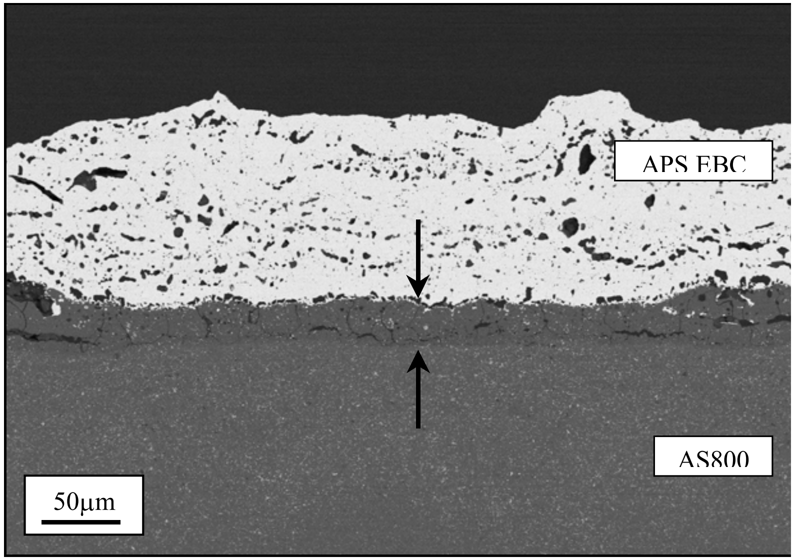
Honeywell

# Test Results Suggest That Further EBC Development Is Required

## Keiser Rig Testing: 500 h @ 2400F, 2 atm $p_{H_2O}$

**uncoated** | **coated**




- **Cracked cristobalite scale thickness similar on coated and uncoated specimen**
- **Latest and future IR&D activities focus on**
  - **better oxygen diffusion barrier capabilities & controlled oxygen reaction**
  - **low cost coating application methods for complex shaped parts**
  - **graded materials development**

Honeywell

# High-Velocity High-Pressure Burner Rig

## Subcontract No. 40000006367 from UT Battelle LCC

# Design Requirements

## Design Requirements

- Test section maximum operating conditions
  - Gas Temperature - 3000°F
  - Equivalent Diameter - 1.0 inch
  - Average  Gas Velocity - 2700 ft/s
  - Partial Pressure of Water Vapor - 70 psia (in combustor)
  - Stress Rupture Test Capability
- Rig intended for long periods of operation (1000's of hours)
  - Operating costs to be minimized
  - Durability natural requirement for extended operation
- Will provide ability to expose most promising ceramics and coatings at environmental conditions typical of turbine nozzles and blades
- Will provide oxidation information at conditions well beyond current experimental database

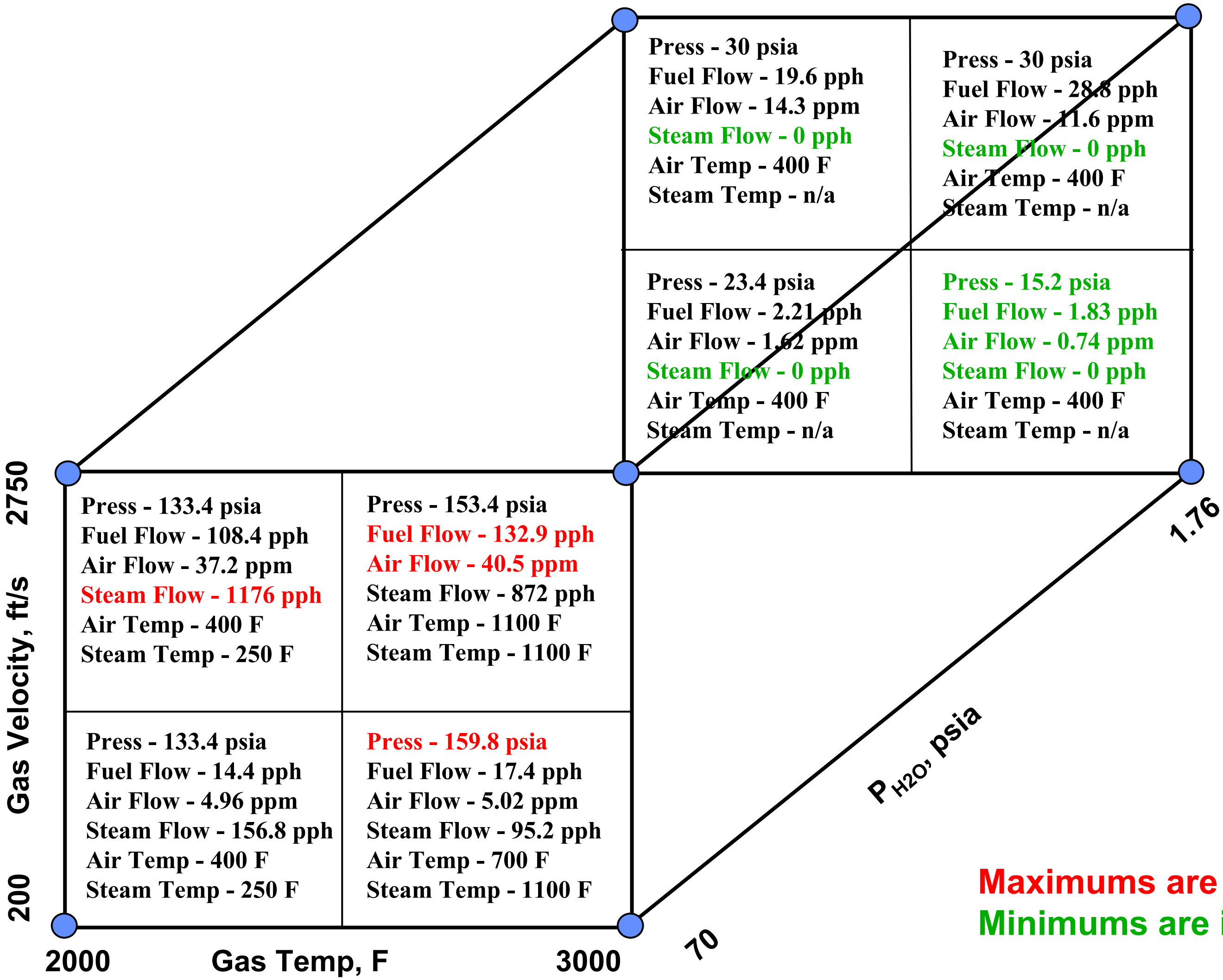
Honeywell

# Operating Conditions

- Natural Gas selected as fuel
  - Higher hydrocarbon content than standard liquid fuels
  - Lower flame radiation to liner walls
  - No nozzle coking problems
  - Supply line in vicinity of proposed test site
- Normal combustion products of natural gas and air cannot achieve the required partial pressure of water vapor at “reasonable” rig operating pressures
- Additional steam injection will therefore be required
- Initial temperature of steam impacts the amount that can be injected because the steam must be heated to 3000°F by the combustion process

Honeywell

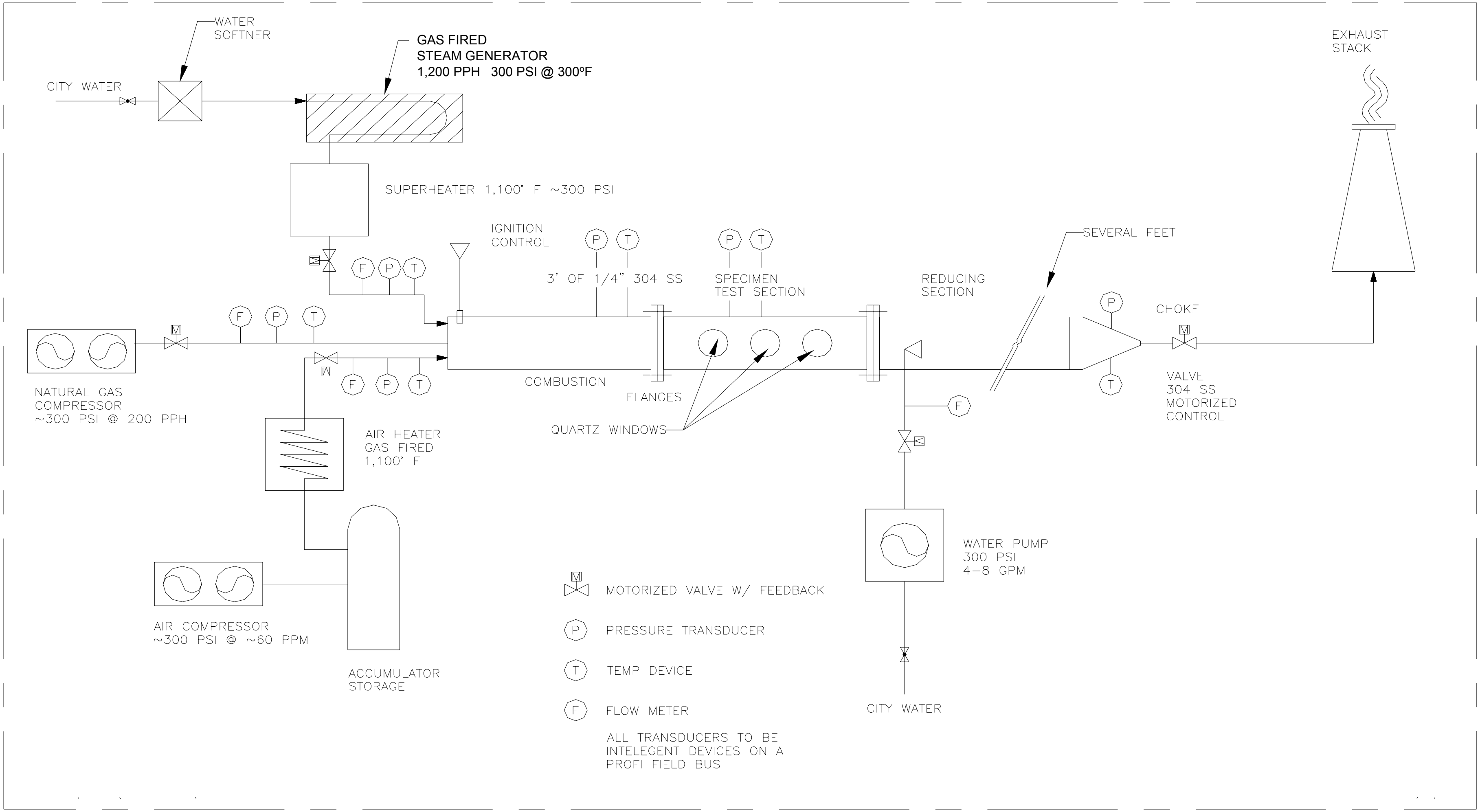
# Operating Envelope Identified




Maximums are in Red
Minimums are in Blue

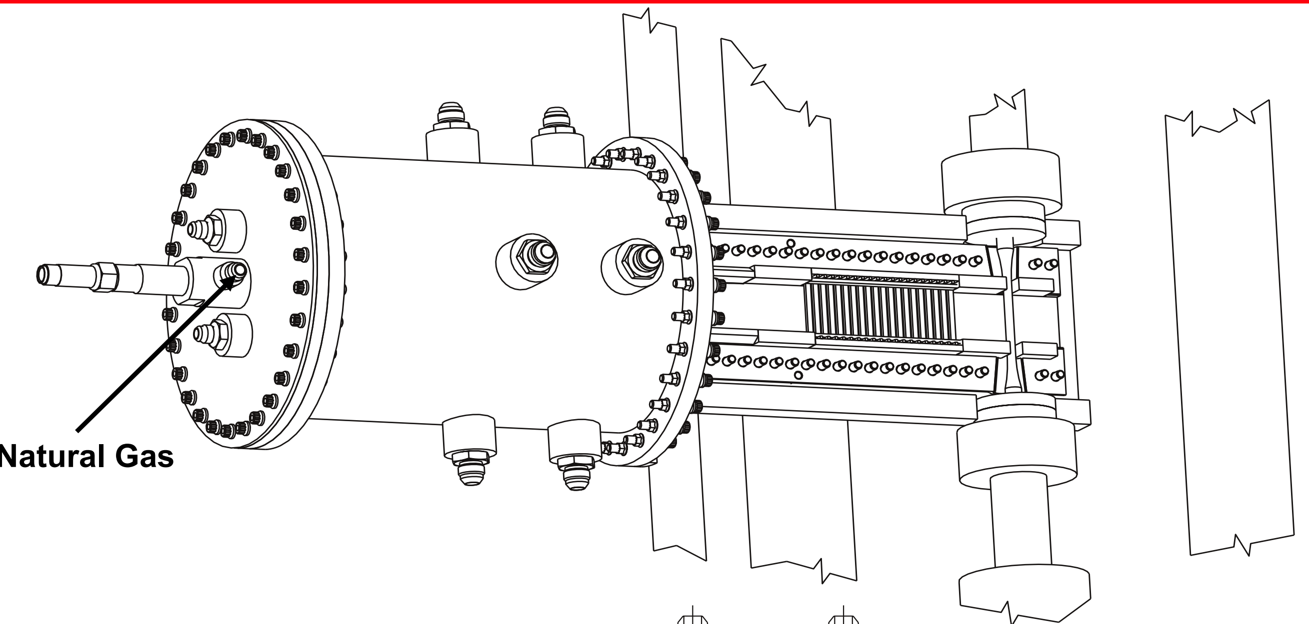
Honeywell

# Simplified Facility Schematic

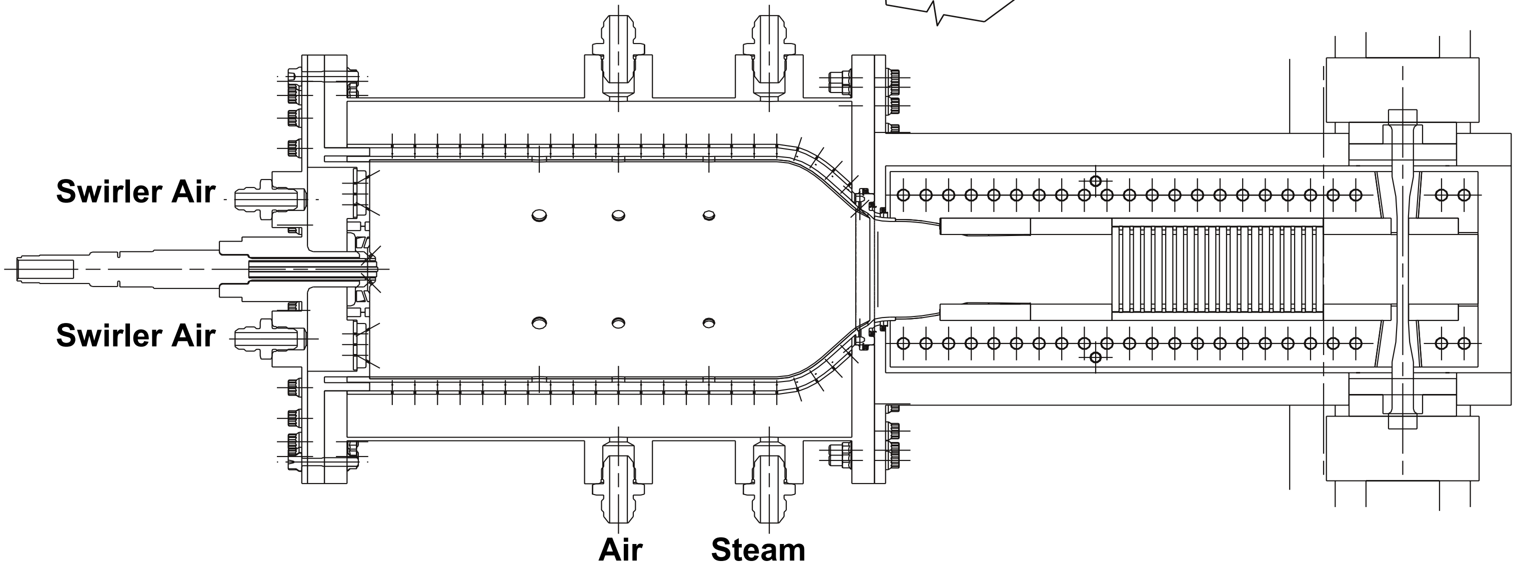



Honeywell

# Current Rig Concept




**Rig Characteristics:**
- **2800F max specimen temperature**
- **2700 ft/s gas velocity (test section entrance)**
- **70 psia max water vapor partial pressure in combustor**
- **1.7” exposed specimen length**
- **Tensile stress rupture test capability**




Honeywell

# Remaining Tasks

- Complete Design FMEA by 15/03/02
- Conduct Design Review (with customer participation)
  - scheduled for March 20, 2002 at ES&S
- Complete facility infrastructure by 06/28/02
- Complete Rig Fabrication by 08/15/02
- 3 months evaluation period of rig operation to follow
- Target date for rig available to ceramic gas turbine community: 01/06/03

Honeywell

# Advanced Microturbine System

## Cooperative Agreement No. DE-FC02-00CH11061

# Motivation and Strategy

- Original Honeywell AMS contract did not address critical ceramic component commercialization requirements
- New program strategy is required to develop the infrastructure and materials & process engineering disciplines necessary to overcome those barriers, which currently prevent structural ceramic component commercialization in advanced heat engines
- Revised program plan provides approach to resolve each of these issues and follows a natural progression based on past DOE-funded efforts at HES&S
- Focus will be on very near-term ceramic component production capability for premium gas turbine applications such as advanced industrial microturbines for distributed power generation
- Effort will draw heavily on "lessons learned" from the problems and successes on previously completed ceramics development and demonstration programs

Honeywell

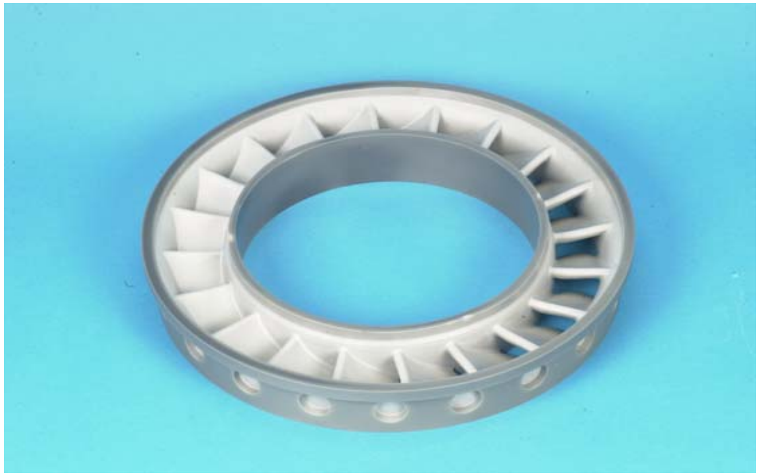
# Work Breakdown Structure

**Honeywell ES&S**
**Advanced Microturbines Systems**
**Related Activities**

- **DOE AMS Program Award 2002 & 2003**
  - **Process Maturation**
  - **Database Generation**
  - **Oxidation Protection**
  - **Project Management**
- **Honeywell IR&D & Potential Government Programs**
  - **Design Processes**
    2002
    Honeywell IR&D
  - **Oxidation Protection**
    2002 & 2003
    Honeywell IR&D
  - **Engine Testing**
    2004 Optional
    DOE AMS Program Phase
  - **Field Evaluation**
    2004 & 2005 Optional
    DOE AMS Program Phase
- **Micoturbine OEM Support**
  (Selected OEM Through Separate Subcontracts)
  - **Ceramic Component Design Consultation**
  - **Life Prediction**
  - **Process Development**
    (Radial Turbine Components)
  - **Parts Fabrication**
  - **Database Generation**
    (Required)
  - **Spin Pit Testing**

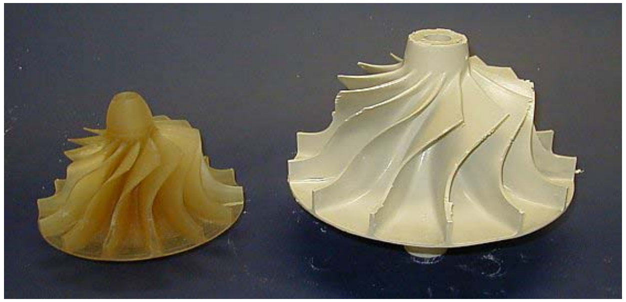
# Mature Low-Cost Near-Net-Shape Manufacturing Of Large Integral Ceramic Components

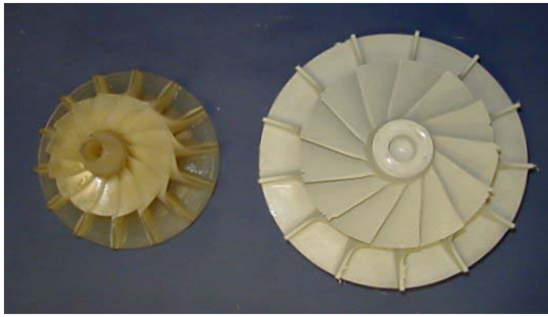
**Nozzle Rings**



**Blisks**

**Radial Turbine Wheels**





N00014-95-2-0006 Honeywell Confidential

# Milestones

| | |
|---|---|
| • Establish Baseline Gelcast Process Map | 3/02 |
| • Gelcast Nozzle & Blisk Tooling Designed & Procured | 7/02 |
| • Optimized Nozzle Ring & Blisk Fab Processes Fixed | 4/03 |
| • Provide “Proof of Consistent Process” Parts | 10/03 |
| • Provide Initial Design Database | 3/03 |
| • Provide Confirmatory Database | 12/03 |
| • Low Cost EBC Approaches Identified | 10/02 |
| • HSBR Screening Tests @ Simulated Engine Conditions | 6/03 |
| • Demonstrate Final Coating Approach On Nozzle Ring | 12/03 |

# Top Level Summary

- **Benefits to Selected Microturbine OEM**
  - Delivery of high quality ceramic components
  - Mature low-cost near-net-shape fabrication process
  - Adequate oxidation protection
  - Joint development of publicly available material design database
  - Access to Honeywell ceramic gas turbine design & life prediction expertise
- **Benefits to the Government**
  - Build upon past investment and successes in ceramic gas turbine technology development
  - Participation of ORNL in key development activities
    - component characterization & database generation
    - oxidation protection system evaluation
  - UDRI (Mechanical Testing in Moist Environment)
  - Northwestern University (Coating Materials Fundamentals)
  - Argonne National Lab (NDE Characterization of EBCs)

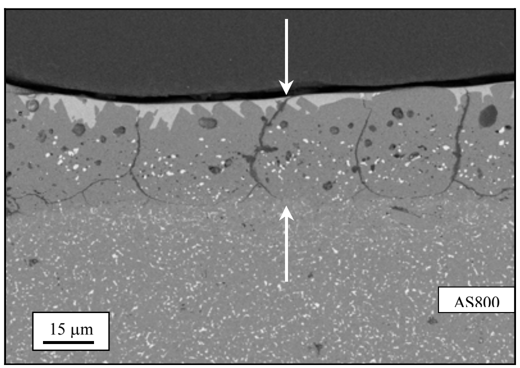
# Summary
# DOE Hot Section Components for AMS

## OBJECTIVES : Characterize Oxidation Behavior of Uncoated and Coated Silicon Nitride Materials

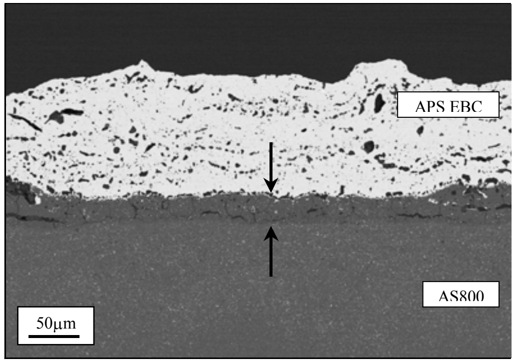
**STATUS:**

- Completed Characterization of Substrate Materials and First Generation EBC in ORNL Keiser Rig

Substrate and EBC Evaluation in Moist Environment Provides




- Fundamental Understanding of Oxidation Processes
- Low Cost Screening of Candidate Coating Systems




**Enables Development of Improved Substrate Materials and EBC Systems**

Honeywell

# Summary
# DOE High-Velocity High-Pressure Burner Rig

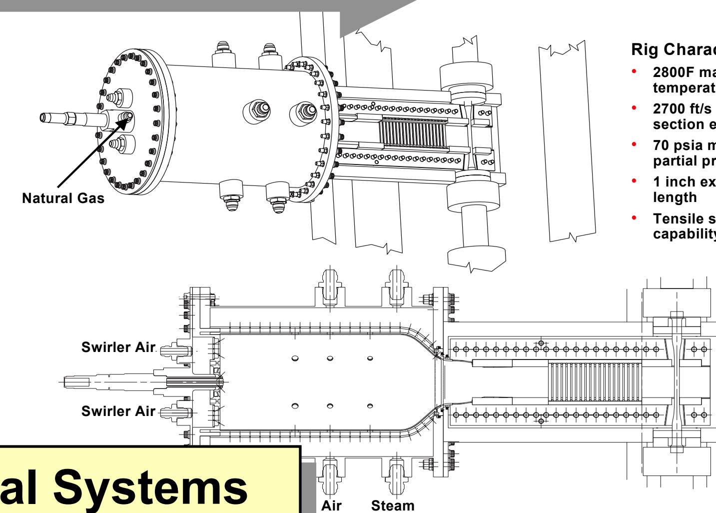
## OBJECTIVES : Develop Burner Rig Simulating Advanced Turbine Engine Environments

**STATUS:**

- Preliminary Design Completed
- Facility Infrastructure Being Built
- Part of DOE Environmental Test Center

**Substrate and EBC Evaluation in Simulated Turbine Environment Provides**

- Fundamental Understanding of Oxidation Processes at Extreme Conditions
- Screening of Candidate Coating Systems prior to High Risk Engine Tests




**Rig Characteristics:**

- 2800F max specimen temperature
- 2700 ft/s gas velocity (test section entrance)
- 70 psia max water vapor partial pressure
- 1 inch exposed specimen length
- Tensile stress rupture test capability

**Final Step in Evaluating Advanced Material Systems**

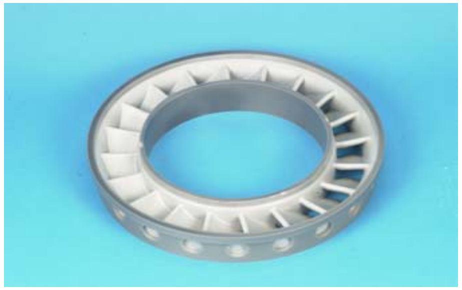
Honeywell

# Summary
# DOE Advanced Microturbine System

## OBJECTIVES : Prepare for Commercialization of Ceramic Turbine Components

**STATUS:**
- Contract Details in Negotiation, FY2002 Funding Released
- Started Low-Cost Net Shape Fabrication Process Development

Process Maturation and EBC Refinement & Evaluation Provide



- Proven Robust Low Cost Process
- Large Integral $Si_3N_4$ Components
- Proven Low Cost EBC Process
- Material Design Database

**Enables Accelerated Commercialization of Ceramics in Small Gas Turbines**

Honeywell